Key parameters of the HEPS booster reached their target values

Peng Yuemei[1,2], Cao Jianshe[1], Chen Jinhui[1], Dong Haiyi[1], He Ping[1], Jiao Yi*[1,2], Kang Ling[1], Kang Wen[1], Li Jian[1], Li Jingyi*[1], Lin Guoping[1], Liu Fang[1], Long Fengli[1,2], Meng Cai[1,2], Qi Xin[1], Qu Huamin[1], Sui Yanfeng[1,2], Wang Sheng[1], Xu Gang[1], Ye Qiang[1], Zhang Jing[1], Zhang Pei[1], Pan Weimin*[1,2]

1 Key Laboratory of Particle Acceleration Physics and Technology, Institute of High Energy Physics, Chinese Academy of Sciences,19BYuquan Road, Shijingshan District, Beijing 100049, China.
2 University of the Chinese Academy of Sciences, 19A Yuquan Road, Shijingshan District, Beijing 100049, China.

Abstract

The High Energy Photon Source (HEPS) is the first fourth-generation synchrotron light source building in China. Its injector consists of a Linac and a full energy booster. The booster captures the electron beam from the Linac and further increases its energy to the same as that required by the storage ring. The full-energy beam could be injected to the storage ring directly or after "high-energy accumulation". On November 17, 2023, it was demonstrated that key parameters of the booster successfully reached corresponding target values. These milestone results were accomplished based on many contributions, including nearly a decade of physics design, years of development and installation of equipment, as well as months of beam commissioning. As measured at the extraction energy of 6 GeV, the averaged beam current and emittance reached 8.57 mA with 5 bunches and 30.37 nm.rad with a single-bunch charge of 5.58 nC, compared with the corresponding target values of 6.6 mA and 35 nm.rad, respectively. This paper presents the physics design, equipment development and installation, and commissioning process of the HEPS booster.

Key words: High Energy Photon Source; Booster; Beam commissioning

*Corresponding author(s)： Jiao Yi， E-mail(s): jiaoyi@ihep.ac.cn;
*Corresponding author(s)： Li Jingyi， E-mail(s): jingyili@ihep.ac.cn
*Corresponding author(s)： Pan Weimin， E-mail(s): panwm@ihep.ac.cn

1. Introduction

As the first fourth-generation synchrotron radiation light source in China, the High Energy Photon Source (HEPS) [1,2] is under construction in the Huairou Science City of Beijing. The HEPS complex consists of a 500-MeV Linac [3], a full energy booster [4], a 6-GeV storage ring with a circumference of about 1.36 km [5], three transfer lines [6], and multiple beamlines and corresponding experimental stations. The layout of HEPS complex was shown in Figure 1. The facility construction started in June 2019, with a scheduled construction period of 6.5 years. Once completed, HEPS would be an important platform to support original and innovative research in the fields of basic and engineering sciences.

As a full-energy injector, the HEPS booster is mainly to increase the energy of electron beam from the Linac to the design energy, 6 GeV, and to provide sufficiently high-quality electron beam for injection to the storage ring. Several milestones of the booster have been reached in the past few years. The physic design and component layout were finalized in December, 2019. The pre-alignment installation of magnet-vacuum units began in March, 2022 and the tunnel

installation of magnet units started in August of the same year. After the equipment installation and conditioning completed in the middle of 2023, the beam commissioning started in the end of July, 2023. And, in November 2023, the electron beam with more than 5 nC of single-bunch charge was successfully ramped to 6 GeV.

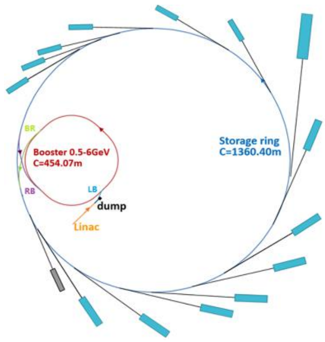

Figure 1. Layout diagram of the HEPS complex (LB is the transport line which connect the Linac and the booster, BR is the transport line that can transfer the beam from the booster to the storage ring, and RB is the transport line that can transfer the beam from the storage ring to the booster).

This paper is arranged as following. In Sec. 2, the selection of key parameters and the evolution of booster lattice design are introduced. The engineering design, equipment installation and conditioning are reviewed in Sec.3, and the beam commissioning is described in Sec. 4. A brief summary is given in the last section.

2. Physics design of HEPS booster

As a fourth-generation synchrotron light source, a multi-bend achromat lattice is adopted in the HEPS storage ring to achieve an ultralow emittance, a natural emittance below 60 pm·rad, and high brightness of up to 1×10^{22} phs/s/mm^2/mrad^2/0.1%BW. On the other hand, this ultralow-emittance design brings a series of physical and technical challenges, which are well reflected in the design of the HEPS booster.

Firstly, the booster should be capable of providing electron bunches with a bunch charge up to 5 nC. Due to the small dynamic acceptance of the storage ring, on-axis swap out injection [7] was selected as the baseline scheme which, however, requires that the booster should provide bunches with high enough charge during each injection process. In this scenario, the maximum charge per bunch reaches about 14.4 nC. In order to reduce the requirement for the charge per bunch injected into the booster at 500 MeV, the so-called "high-energy accumulation" scheme [8] was proposed.

The implementation of “high-energy accumulation” scheme requires adding a high-energy transport line that can transfer the beam from the storage ring to the booster and a high-energy injection system to support off-axis injection in the booster. When the electron beam in the storage ring needs to be refilled, the bunch with the lowest charge will be extracted and injected into the booster. Then, the bunch will merge with an existing bunch in the booster that has been injected from the linac and accelerated to 6 GeV. After more than 3 damping times, this merged bunch will be extracted from the booster and reinjected to the storage ring. In this scheme, the booster is used as an accumulator at 6 GeV.

Even so, the charge per bunch injected into the booster at 500 MeV is still required not less than 2.5 nC. Considering difficulties in the initial commissioning of the storage ring, the charge-per-bunch injected into the booster at 500 MeV and ramped to 6 GeV were increased to

6.25 nC and 5 nC respectively, which means a transmission efficiency of 80% during the ramping process is required. Such a high bunch charge brings challenges to both the booster and the Linac.

Since on-axis injection was adopted for the booster at 500 MeV, it is required that the Linac should provide electron pulse with charge not less than 6.25 nC. Considering the weak radiation damping and collective instabilities at 500 MeV, studies had been conducted to investigate the bunch charge threshold at this energy. Studies indicates [9-12] that the transverse mode coupling instability (TMCI) threshold is a key factor limiting the charge per bunch at low energies, and increasing the momentum compaction factor is an effective way to increase the TMCI threshold. As a result, FODO cells are selected as the basic lattice structure [4]. With such a simple and reliable structure, a relatively large momentum compaction factor, about 3.7×10^{-3}, is achieved in the design, yielding sufficient high bunch charge threshold.

In addition, based on considerations of mitigating the impact of the booster's operation on beam orbit fluctuations in storage ring, and simultaneously implementing beam commissioning of the booster and tunnel installation of the storage ring, it was decided to locate the booster in a separate tunnel, with a circumference about one-third of the storage ring.

After evolution of a few years, the booster lattice was finalized in the end of 2019. The lattice has four super-periods. Each super-period consists of 14 standard FODO cells and matching sections at both ends, containing 32 dipole magnets, 37 quadrupole magnets, and 17 sextupole magnets. Each period provides a dispersion-free straight section of approximately 8.8 m, for low-energy injection, extraction, high-energy injection, and RF system equipment, respectively. The Lambertson septum was chosen in HEPS booster design, in order to keep the tunnel of Linac, booster, and storage ring on the same horizontal plane, injection and extraction of the booster occur in the vertical plane. In the high-energy injection design, a dedicated π-section was designed, with 2 kickers placed at both ends to form a local bump. Compared to conventional 4-kicker injection scheme, this scheme reduces the number of kickers, and also the impedance budget and cost. In addition, in the high-energy extraction design, 4 fast bumper magnets [13] were placed in the design to form a local bump to reduce the required kicker strength. The optics of one super-period in the HEPS booster was shown in Figure 2.

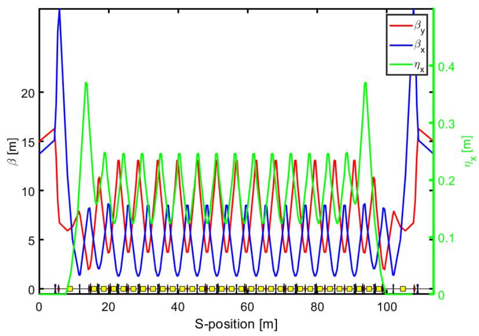

Figure 2. Layout and optics of a super-period in the booster.

Studies on transmission efficiency during injection and ramping [14], fringe field effects [15], eddy current effects during ramping process [16], and error effects on beam dynamics [17], were also performed to ensure that there are no show-stoppers in beam dynamics point of view. Some key parameters of the booster are listed in Table 1.

3. Equipment development and commissioning preparation

Aiming to build a high performance full-energy injector, the booster is designed based on

considerations both on robustness and advancement. After iterative optimization, the accelerator physics design and equipment technical design were finalized by the end of 2019 [13, 18-24].

There are mainly 4 types of magnets installed in the booster, including dipoles, quadrupoles, sextupoles and orbit correctors. The iron cores of these magnets are made of 0.55-mm thick silicon-steel laminations to mitigate eddy current effect during energy ramping. All these magnets are carefully sorted to minimize field uniformity induced effects [25]. Each type of magnets (excluding orbit correctors) are grouped into several families. The dipoles in each arc are set as a family, there are 4 groups of dipoles. The quadrupoles are divided into 8 families and the sextupoles were grouped in 6 families. Each family of magnets are connected in series and energized by a same power supply. All of these power supplies (PSs) are synchronized during ramping up and down processes. The ramping processes are guided by a pre-generated table. The ramping table is produced according to the I-BL curve determined by magnetic field measurements. The ramping process can be programed to stop and stay at any energy between the injection and extraction energies and work as a storage ring. This feature enables people to conduct energy-dependent machine studies and ramping curve optimization. As presented in the following picture (Figure 3). The Beam energy stay at 6GeV, the strength of QD4 was optimized for adjusting the tune, and based the optimized strength, the ramping curve update online. Using the in-house developed controllers, the magnet PSs have been working reliably with both small dynamic tracking errors and high stability in DC mode.

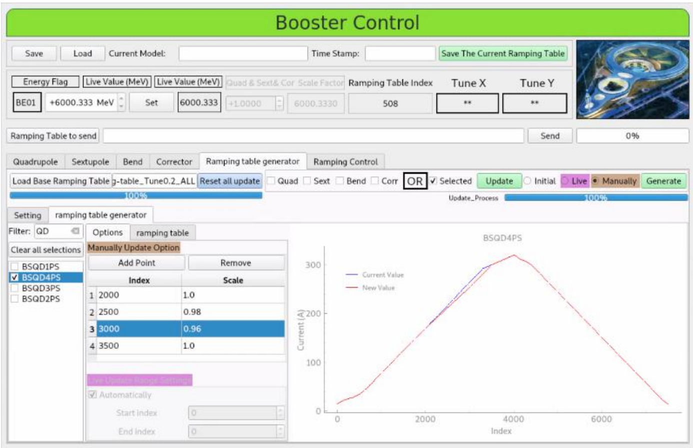

Figure 3. Interface of HEPS booster control application.

The vacuum chamber of the booster is mainly made of 316L type of stainless steel to gain lower than 1.02 of permeability after manufacturing. The thickness of the chambers is selected as 0.7 mm to reduce eddy current induced by the varying magnetic field during energy ramping. Because the booster is designed as a charge accumulator at 6 GeV, the maximum averaged beam current could be higher than 13 mA. In this scenario, the estimated heat load produced by the synchrotron radiation could be more than 290 W/m. To avoid deformation and protect critical equipment, water-cooling on the vacuum chambers is adopted.

The booster is designed to be equipped with six PETRA-type 5-cell normal conducting RF cavities working at 499.8 MHz. Only five of them were installed in current stage, leaving the other one for off-line testing and probably to be used by the storage ring during vacuum cleaning. The RF voltage and phase can be ramped with magnet PSs. Due to lacking of High-Order Modes (HOMs) dampers, this type of cavities are suspected rich in HOMs when operating with beam. Previous studies [26] indicate that the growth time of coupled-bunch instabilities driven by

dangerous HOMs would be very short. The planned curing method includes adjusting the temperature of cooling water and the resonant frequencies of the cavities. A bunch-by-bunch feedback system was also planned.

Lambertson type septum magnets are used to guide the electron beam entering the booster from the transport line during injections, and vice versa during extraction. Slotted-pipe kickers, driven by LC series resonant pulsed power supplies, are employed to kick the electron beam into the booster acceptance when injection, and out of the booster for extraction. The pulse length of the kickers allows filling 5 evenly distributed buckets, or any combination of these five buckets, in the booster ring.

An equipment installation experiment was conducted prior to the magnet-unit pre-alignment and vast installation in the tunnel to verify the layout design. Installation procedures as well as wiring and water-cooling arrangement and connection are optimized and finalized with the aid of this experiment. The vast installation of the pre-aligned magnetic units, which was started about five months earlier, was launched in August 2022. After about five months of installation, and six months of wiring and equipment testing, the booster was ready to be commissioned in July 2023.

A rich set of high-level applications (HLAs) has been developed by the HEPS physics team. All these HLAs are based on the independently developed application framework *Pyapas* [27, 28]. Thanks to the modular design, the principle based on physical quantities and the ability of running simulation models online from *Pyapas*, the development efficiency and reliability of the HLAs have been greatly improved. These features of the HLAs allow people to knob the beam more intuitively.

4. Beam commissioning

The beam commissioning of the booster was started on July 25, 2023. Illustrated by Figure 4, the commissioning process can be roughly divided into three stages. In first couple of days, efforts were made to make the beam circulate in the booster ring and captured by the RF buckets. In this stage, we observe the beam injection situation through the BPM row data. By scanning the kicker strength and fine-tuning the correctors' strength near the injection point, the beam can accumulate about 20 turns. After adjusting the set of injection energy in the booster, the beam can accumulate more than 25 ms. Based on the theoretical response matrix and the TBT data, the orbit was preliminary corrected. Then, the sextupole magnets was powered on, and the RF was turned on, beam accumulation achieved after RF frequency correction. The beam was also managed to be ramped to 6 GeV in this stage.

In the following stage, which toke about 2 months, it is mainly focused on optimizing the beam transmission efficiency during injection and ramping processes. Equipment performance improvement was also performed in this stage. A bunch charge lower than 3 nC from the Linac is used to reduce radiation dose. A total transmission efficiency of above 80% was achieved with this configuration in late September. For improving the transmission efficiency, beam dynamics was optimized both in the injection and ramping process. Including but not limited to optimize the energy, position, angle and distribution of injected beam, adjust the RF voltage and phase, optimize the delay time of PSs, correct the closed orbit and tune. During the ramping process at this stage, each RF cavity needs to provide a voltage greater than 1.6MV, and the power used is almost at its limit. This makes it prone to vacuum protection or open loop, thus imposing several restrictions on the energy ramping operation.

In the 3rd commissioning stage, after about 20 days of equipment installation, high bunch charge was mainly pursued. The Linac was tuned to provide more than 8 nC at its exit. With the Twiss parameters matched at both ends of the low-energy transport line based the beam parameter at its entrance, the bunch charge has been increased to higher than 6.5 nC at the end of the transport line. Due to these efforts, a bunch charge of more than 5 nC was ramped to 6 GeV on November 6, 2023. Since then, multi-bunch mode commissioning and repetition rate improvement were carried out. By November 17, all the target values proposed by the preliminary design report has been reached. The results are listed in Table 1. In the table，the beam energy directly calibrated by the dipole strength (I-BL)， the emittance and energy spread directly given by the synchrotron light monitor， the beam current and bunch charge given by DCCT and BCM. When measure the beam current and bunch charge, we conducted 11 times measurements and provided the statistical values. When measuring the repetition rate, we calculated how many cycles were completed in half a minute. 1.07Hz is the highest value achieved now, and the repetition rate below 1.07Hz is acceptable. These results indicate that the booster is qualified for subsequent commissioning of the storage ring. Since the storage ring is still in equipment installation phase, the “high-energy accumulation” scheme was not tested in this period of commissioning. It is worth mentioning that the coupled-bunch instabilities driven by dangerous HOMs didn’t occur in the beam commissioning process and the bunch-by-bunch feedback system has not started working yet.

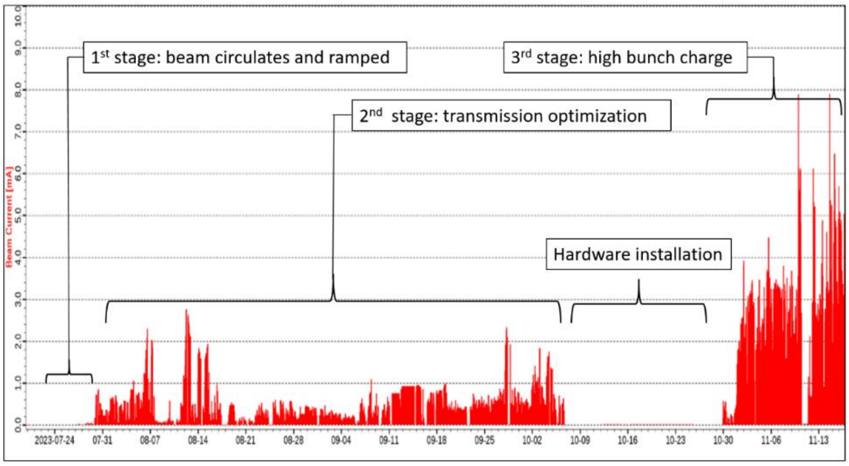

Figure 4. Historical curve of beam current during the booster commissioning process.

During the commissioning, the most challenging goal is to achieve a single bunch charge above 5 nC at 6 GeV. In response to this challenge, efforts have been made in two aspects, including improving the transmission efficiency in the whole process and increasing the pulse charge from the Linac. In improving the transmission efficiency, beam dynamics was optimized both horizontally and longitudinally. Considering the horizontal factors, the entrance angle, position, distribution of the injection beam were scanned for their optimal. The orbit and optics errors of the booster were also adjusted to increase the capture rate and ramping transmission rate. The beam lost mainly occurred below 1GeV, and many efforts have been made in these energy points, such as the tune and the closed orbit was optimized to stable region, which shown in Figure 5. We also optimized the optics with the theoretical design lattice as the target at 6GeV. After correction, the beta-beating is about 2% (RMS) both in horizontal and vertical plane (Figure 6).

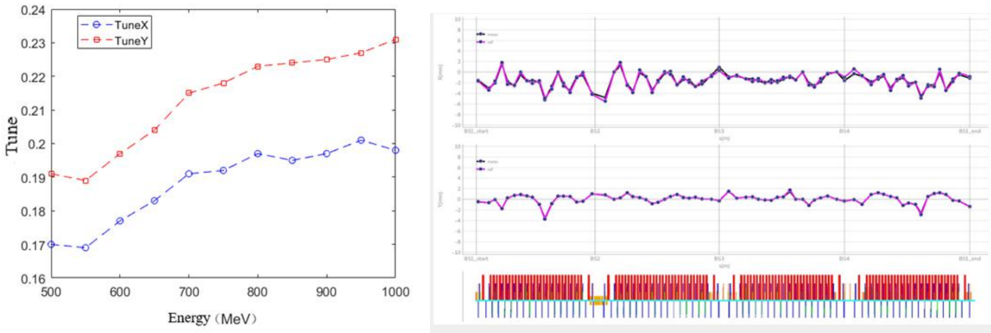

Figure 5. The tune (left) and the closed orbit (right) in HEPS booster

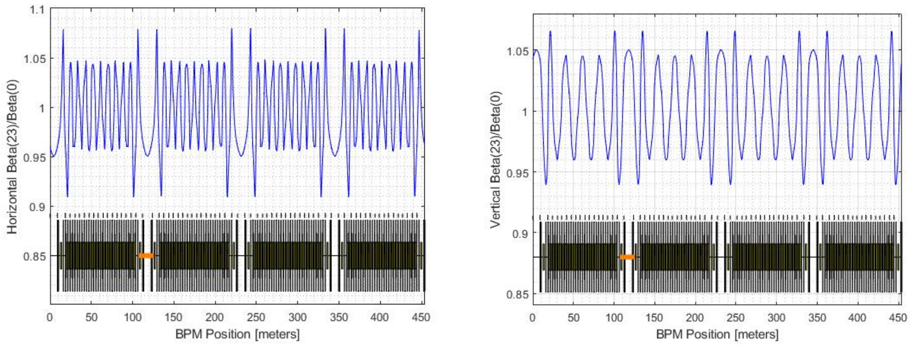

Figure 6. The beta-beating in the HEPS booster at 6GeV.

On the longitudinal side, the energy of the injection beam was carefully matched with that of the booster by adjusting the injection energy settings of the booster. The voltage and phase of RF cavities are the other longitudinal factors that impacts the efficiency. They were tuned for best capturing. The total transmission efficiency was finally reached over 80%, calculating using the amount of the charge at the end of the transport line and that when the booster ramped to 6 GeV.

Finally, with sufficient pulse charge from the Linac, a single bunch charge of over 5 nC at 6 GeV was successfully achieved. Figure 7 gives a typical charge transmission in an injection-ramping cycle.

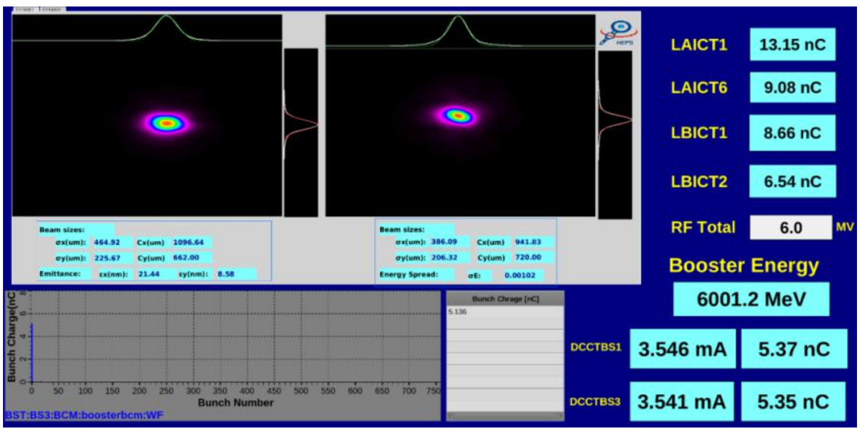

Figure 7. Screenshot of Beam status monitoring (LAICT1 is the ICT downstream of the electron gun, LBICT1 is an ICT at the entrance of the transport line, LBICT2 is an ICT at the end of the transport line, “RF total” means the total RF voltage, DCCTBS1 and DCCTBS3 are two DCCT in the booster.)

Table1 Key parameters of the HEPS booster

Parameters	Units	Design value	Target value	Measured value
Energy	MeV	500 – 6000	500-6000	6001.20 ± 0.30
Repetition rate	Hz	1	~1	1.07
Max. beam current @500MeV	mA	11@10bunches	8.25@5 bunches	Avg.value：8.951 Max. value：11.489
Max. beam current @6GeV	mA	13（w/ high energy accumulation）	6.6@5 bunches	Avg.value：8.571 Max. value：9.367
Bunch charge@6GeV	nC	≥2	≥5	Avg.value：5.409 Max. value：5.650
Natural emittance@6GeV	nm	35	≤35	30.37 ± 0.30 @ 5.58 ± 0.05 nC
Energy spread@6GeV	%	0.096	~0.1	0.0994 ± 0.0029 @ 5.58 ± 0.05 nC

5. Summary

After nearly a decade of physics design, years of development and installation of equipment, as well as months of beam commissioning, the HEPS booster recently reached the commissioning goal of bunch charge over 5 nC at 6 GeV. This validates the physics design and demonstrates that the equipment performance meets the design requirements. The beam parameters of HEPS booster can meet the requirements for subsequent commissioning of the storage ring. The performance improvement of the booster will be continued. Besides severing as a full energy injector, the HEPS booster can be operated as a storage ring at any energy between 0.5 and 6 GeV, for beam physics experiments of interest.

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